DEVELOPMENT AND CHARACTERIZATION OF COMPOSITES CONSISTING OF WOVEN FABRICS WITH INTEGRATED PRISMATIC SHAPED CAVITIES

R. Geerinck[1*], I. De Baere[1], G. De Clercq[2], J. Ivens[3], J. Degrieck[1]

[1]Department of Materials science and engineering
Ghent University, Technologiepark-Zwijnaarde 903, 9052 Zwijnaarde, Belgium
Email: Ruben.Geerinck@ugent.be, Ives.DeBaere@ugent.be, Joris.Degrieck@ugent.be

[2]Department of Textiles
Ghent University, Technologiepark-Zwijnaarde 907, 9052 Zwijnaarde, Belgium
Email: geert.declercq@ugent.be

[3]Department of Metallurgy and Materials Engineering
KU Leuven, Kasteelpark Arenberg 44 bus 2450, 3001 Leuven, Belgium
Email: Jan.Ivens@mtm.kuleuven.be

ABSTRACT

Composites are extensively used in automotive, construction, airplanes, wind turbines etc. because of their good mechanical properties such as high specific stiffness, high specific strength and resistance against fatigue. The main issues with composites are delamination and the manual labour in the production process. If hollow structures like stiffeners need to be manufactured, these problems become even more apparent. As a result, there is a lot of interest in woven fabrics with integrated prismatic shaped cavities for composites as they reduce the manual labour, have a higher resistance against delamination and can lead to special properties and applications. In this work several of these woven fabrics with integrated prismatic shaped cavities are designed and produced in high-tenacity polyester yarns. Then, the possibility to use these fabrics in composites is explored: reproducibility of the production process is assessed and static testing is performed. A reproducible production process is developed and static testing shows promising results.

1 INTRODUCTION

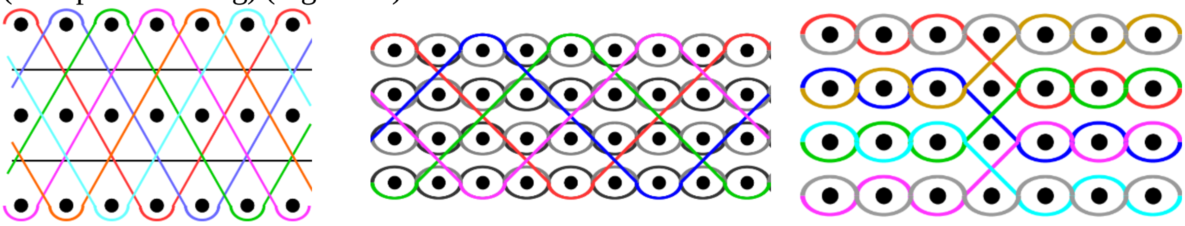
There is a lot of interest in complex 3D woven fabrics for composites because they can lead to special mechanical properties and applications. The two main advantages are the improved resistance against delamination and the reduction of manual labour. Since the fabrics are produced in one single run, a stacking sequence is not needed as this is already implemented at the weaving loom and all the different layers are connected to each other to improve the resistance against delamination. This work focusses on the production and processing of hollow 3D woven fabrics.

The term '3D woven fabrics' is widely used but a lot of different classifications have been given to the term. This due to the fact that there are many different configurations and possibilities within the weaving technology. For example Fukuta and Aoki [1] took into account the methods of manufacturing, including the dimension of the structure, fabric architecture, yarn dimensions and directions within the preform. Khokar [2] on the other hand defined that a 3D woven fabrics should have shedding in the fabric length direction and in the through-the-thickness direction. Many different classification and definitions can be found in literature [3]. The most general classification is given by Chen (Table 1) [4]. This overview refers to the woven fabric itself and not the production method or the type of weaving loom.

	Structure	Architecture	Shape
1	Solid	Multilayer Orthogonal Angle interlock	Compound structure, with regular or tapered geometry
2	Hollow	Multilayer	Uneven surfaces, even surfaces, and tunnels on different levels in multi-directions
3	Shell	Single layer Multilayer	Spherical shells and open box shells
4	Nodal	Multilayer Orthogonal Angle interlock	Tubular nodes and solid nodes

Table 1. 3D textile structures and weave architecture [4].

The authors of this research, however, define a multilayer fabric as a woven fabric where multiple yarn layers or woven layers are connected to each other. Chen [4] refers to these fabrics as a solid structure with a multilayer, orthogonal or angle locked architecture (row 1 in Table 1). Within the multilayer fabrics three different categories are defined (Figure 1). The first one is a fabric with non-crimp yarn layers where the yarn layers are held together with a yarn system in the third dimension (z-direction) (Figure 1a). The second type of multilayer fabric is a fabric consisting of multiple woven layers again held together with a yarn system in the third dimension (Figure 1b). In these first two categories the yarn system in the third dimension can have different geometries. The yarns can penetrate through all the layers (through the thickness) or only a part (layer by layer) and can penetrate the different layers perpendicular (orthogonal) or at an angle (angle locked) [5]. In Figure 1a and b, a through the thickness angle locked connection is displayed. The third and last category is a multilayer fabric where the woven layers are no longer connected with a yarn system in the third dimension but are connected due to the fact that the warp yarns shift from one layer to another and thus interlocking the different layers together (=warp interlocking) (Figure 1c).

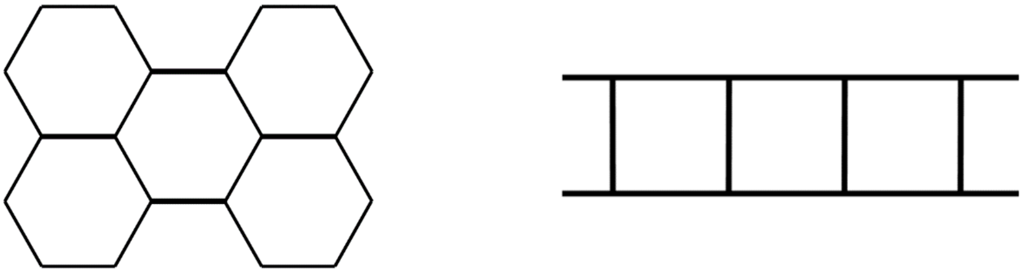


a) NC yarn layers b) Woven layers c) Warp interlocking

Figure 1. Overview of the different categories of multilayer fabrics.

Once cavities are introduced in the woven fabrics, the authors will refer to the fabrics as woven fabrics with integrated prismatic shaped cavities. Chen [4] refers to these fabrics as ‘hollow fabrics’ (row 2 Table 1). The term ‘hollow fabrics’ however is more comprehensive. Shell fabrics, the more common spacer fabrics… can also be classified as hollow fabrics.

Within these woven fabrics with integrated prismatic shaped cavities two categories can be defined (Figure 2). The first category has profiled surfaces (Figure 2a), the second has flat surfaces (Figure 2b). The connections between the surfaces of the fabrics can differ from Figure 2.



a) Profiled surfaces b) Flat surfaces

Figure 2. Overview of the different categories of woven fabrics with integrated prismatic shaped cavities.

1.1 Profiled surfaces

A method for the production of woven fabrics with integraded prismatic shaped cavities with profiled surfaces is well described by Chen et al. [3, 6, 7]. These fabrics are refered to with many different names:

- Chen et al. [6]: 3D honeycomb structures
- Unal [7]: 3D spacer fabrics with uneven surfaces
- Chen et al. [3]: hollow woven fabrics with uneven surfaces.

The production of these fabrics is based on the multilayer principle, where the adjacent layers of fabrics are combined and separated at arranged intervals, as shown in Figure 3 [3].

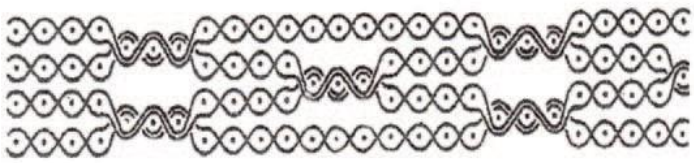


Figure 3. Possible weaving pattern for woven fabrics with integrated prismatic shaped cavities with profiled faces [3].

Chen et al. [6] produced several differend fabrics using this method. The used yarn was a cotton 14.8/3 tex with a weft and warp density of 7.87 threads/cm. The fabrics are produced on a dobby weaving loom on a width of 30.48cm [8].

Using hand lamination Chen et al. [6] made a composite out of these fabrics with an epoxy resin. An opening device is developed with two sets of metal wires to open the fabric after impregnation and achive the correct dimensions.

1.2 Flat surfaces

The second type of woven fabrics with integrated prismatic shaped cavities has flat surfaces. These fabrics can be produced in various ways. The first way is described by Wang et al. [9]. On a small rapier loom with six warp yarns (2200 tex glass fiber) these fabrics were produced with a core heigth of 10 and 20mm. After hand lamination with epoxy resin, foam was needed in the cavities of the fabric to achive the proper structure.

A second way of producing this type of fabric is given by Mountasir et al. [10]. For this process a terry weaving mechanism, in addition to a fabric storage mechanism and a warp pull-back system is necessary. While the crosslinks are woven, the warp yarns of the outer layers are floating (e.g. not participating in the weaving process) (Figure 4b). When the crosslinks are woven, the floating warp yarns are pulled back towards the warp beam making this process a discontinuous production process (Figure 4c). This fabric is woven on a standard double-rapier weaving loom VTR-23 (N.V. Van de Wiele, Belgium) with a warp density of 200 yarns per 10cm. To make these machine movement possible, major adaptations on the loom are necessary. A description of the loom and the adaptations is given by Badawi [11].

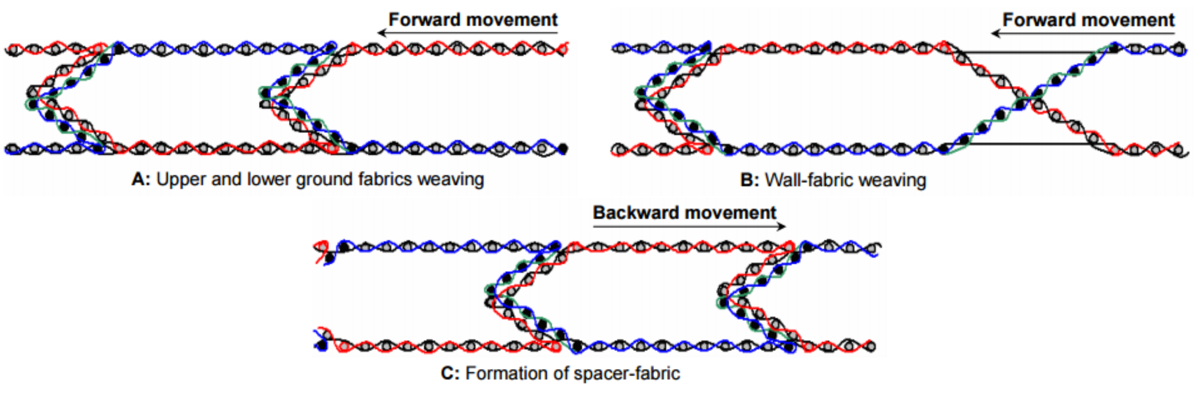


Figure 4. Different phases during production [11].

The yarn used for this fabric is a hybrid glass/PP yarn. With a thermoforming process a composite is made out of the woven fabric. The main difference with the previous discussed woven fabrics with integrated prismatic shaped cavities is the thermoplastic matrix that is inserted in the farbic during the weaving process.

A whole other catergory of woven fabrics are the spacer fabrics. Here the two woven surfaces are held at a distance by lose pile yarns. The main difference with the woven fabrics with integrated prismatic shaped cavities is that the connection is made by lose yarn and not by woven connection [12]. 3D shell fabrics and 3D nodal fabrics are not part of this reseach and will not be futher discussed (row 3 and 4 in Table 1). More details can be found in [3].

2 WOVEN FABRICS

For this reseach two different types of fabrics have been produced in cooperation with 3D Weaving. The first fabric is a woven fabric with integrated prismatic shaped cavities with profiled faces as shown in Figure 5. A total of seven variants have been produced with different amount of layers and geometries. The fabric displayed in Figure 5 has alternating five or six (5-6) hexagonal cavities on top of each other. Other fabrics consist of 2-3 or even 1-2 hexagonal cavities on top of each other. All these different geometries are woven with different amounts of layers so the impact of the number of layers and the geometry can be investigated.

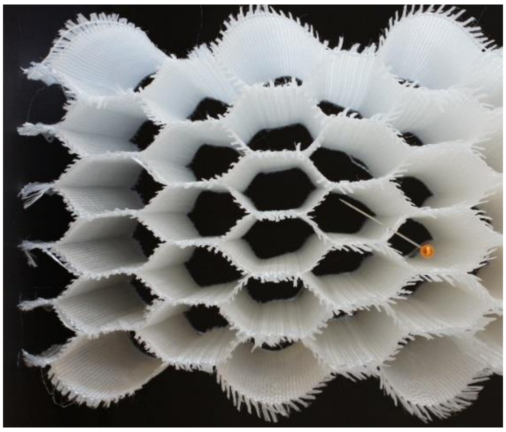


Figure 5. Woven fabric with integrated prismatic shaped cavities with profiled surfaces; a pin needle illustrates the dimensions.

The second type of fabric is a woven fabric with integrated prismatic shaped cavities with flat surfaces as shown in Figure 6. Two different geometrical structures have been produced: a fabric with one squared cavity (Figure 6) and a fabric with two squared cavities on top of each other.

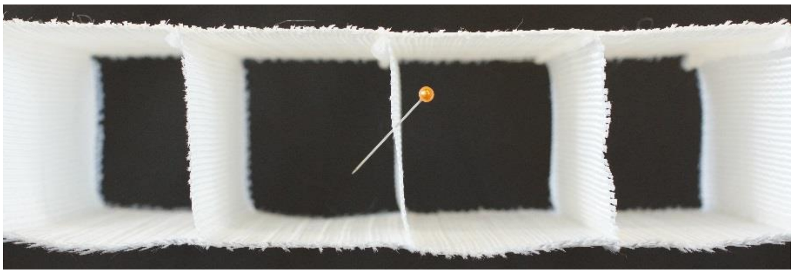


Figure 6. Woven fabric with integrated prismatic shaped cavities with flat surfaces; a pin needle illustrates the dimensions.

Both types of woven fabrics with integrated prismatic shaped cavities are produced at industrial speed on a standard loom with minor adaptations and have a width of 1.5m. In comparison to Mountasir et al. [10] this production process is continuous process with less adaptations.

All fabrics are made in high tenacity (HT) polyester yarns for two main reasons. The first one is the ease of handling. The for composites more conventional glass or carbon yarns have a low resistance against friction and are more difficult to process on a weaving loom. Due to the high density of yarns in the loom (120yarns/cm) and the adaptations that were needed during the production of these complex fabrics a HT-polyester yarn was chosen to avoid the above mentioned problems. A second advantage is the wieght/cost of the yarn with respect to glass and carbon.

3 COMPOSITE PRODUCTION

A lab scale production process has been optimized for one composite of each fabric type with a polyester resin. For each composite a mould is developed to achieve a reproducible production process. The samples of both fabrics are displayed in Figure 7. For the upscaling of the production process further investigation is needed.

For the composites made out of a woven fabric with integrated prismatic shaped cavities with profiled surfaces also foamed specimens have been produced. The used foam is a two-component PUR foam with a density of 75kg/m³.

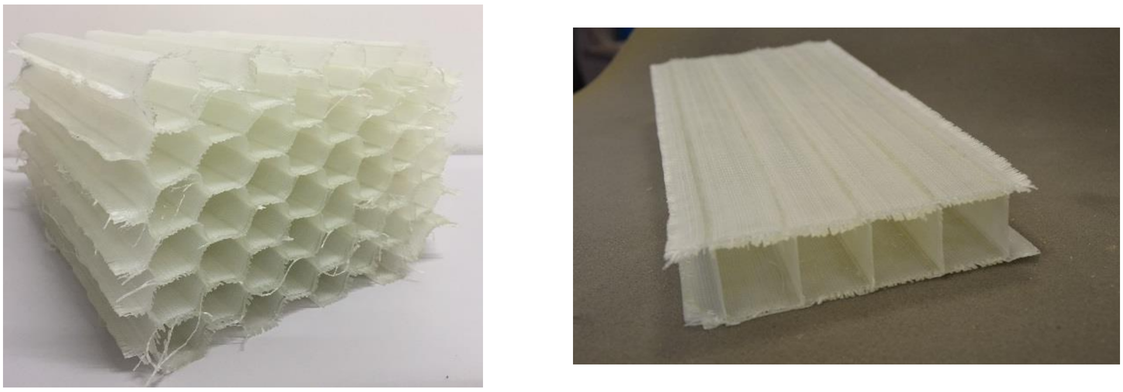


Figure 7. Lab scale composites of the woven fabrics with integrated prismatic shaped cavities.

4 BENDING TESTS

As first initial tests, three point bending tests have been performed for quality control of the production process and for the ease of interpretation of the results. Larger panels made out of these fabrics will also be most likely subjected to bending.

All three point bending tests have been performed on an Instron 5800R tensile machine with a load cell of 10kN at a displacement speed of 1mm/min.

4.1 Woven fabrics with integrated prismatic shaped cavities with profiled surfaces

The bending tests on the composites of the woven fabrics with integrated prismatic shaped cavities with profiled surfaces are conducted on a single hexagonal cavity because of the limited dimensions of the produced lab scale specimens. Since the height of a composite of 5-6 hexagonal cavities on top of each other is 15cm, a large specimen is needed to test the specimen in bending and not in shear.

Both an unfilled and a filled hexagonal cavity have been tested in bending. The specimens have a length of 250mm, a width of 29mm and a height of 25mm. The distance between the supports is 200mm. The results of both bending tests are shown in Figure 8. The specimen without foam will fail due to local indentation at the indenter as can be seen in Figure 9. The specimen with foam reaches much higher forces as the foam prevents local indentation at lower forces. This specimen first goes in bending before local indentation starts at higher forces.

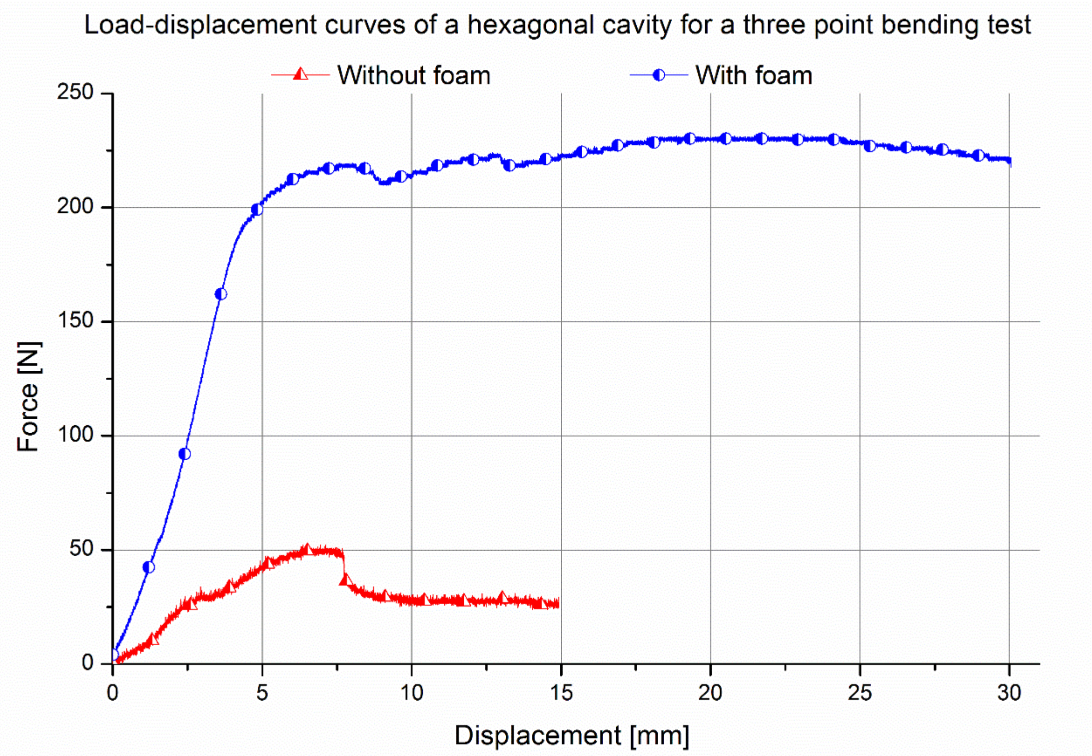
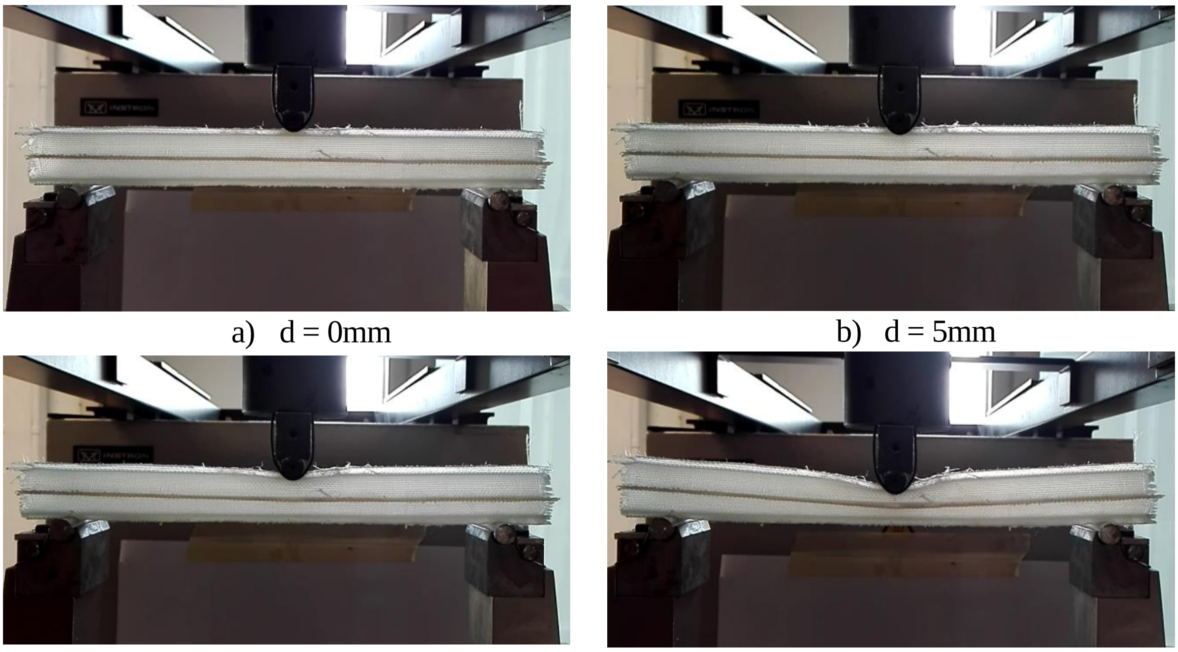


Figure 8. Comparison of a filled and unfilled hexagonal cavity for a three point bending test.



a) d = 0mm

b) d = 5mm

c) d = 8mm

d) d = 15mm

Figure 9. Illustration of the local indentation of an unfilled hexagonal cavity at the indenter at different displacements.

4.2 Woven fabrics with integrated prismatic shaped cavities with flat surfaces

Two bending tests have been performed on composites made out of a woven fabric with integrated prismatic shaped cavities with flat surfaces. The first one is on a single squared cavity, the second one is on two square cavities, both without foam. The specimen consisting of a single cavity has a length of 350mm, a width of 65mm and a height of 35mm. The second specimen with two cavities has the same length and height but has a width of 98mm. The distance between the supports is 300mm. For these tests a larger indenter is needed because of the dimensions of the specimen with two square cavities.

The results for the two bending tests are displayed in Figure 10. Both specimens fail due to local indentation at the indenter. Figure 11 shows the local indentation at different displacements for the specimen with a single cavity. The specimen with two cavities shows a higher peak force, an increase of 50%, before local indentation starts. This is due to the fact that this specimen has three vertical connections between the outer layers in comparison to the specimen with a single cavity that only has two vertical connections.

What could be noted is the residual strength after the three point bending test and the toughness of the polyester-polyester material combination (Figure 11e). Furthermore, the specimens do not shown any splintering of the material. This in contrast to the typical brittle behaviour of a glass or carbon composite.

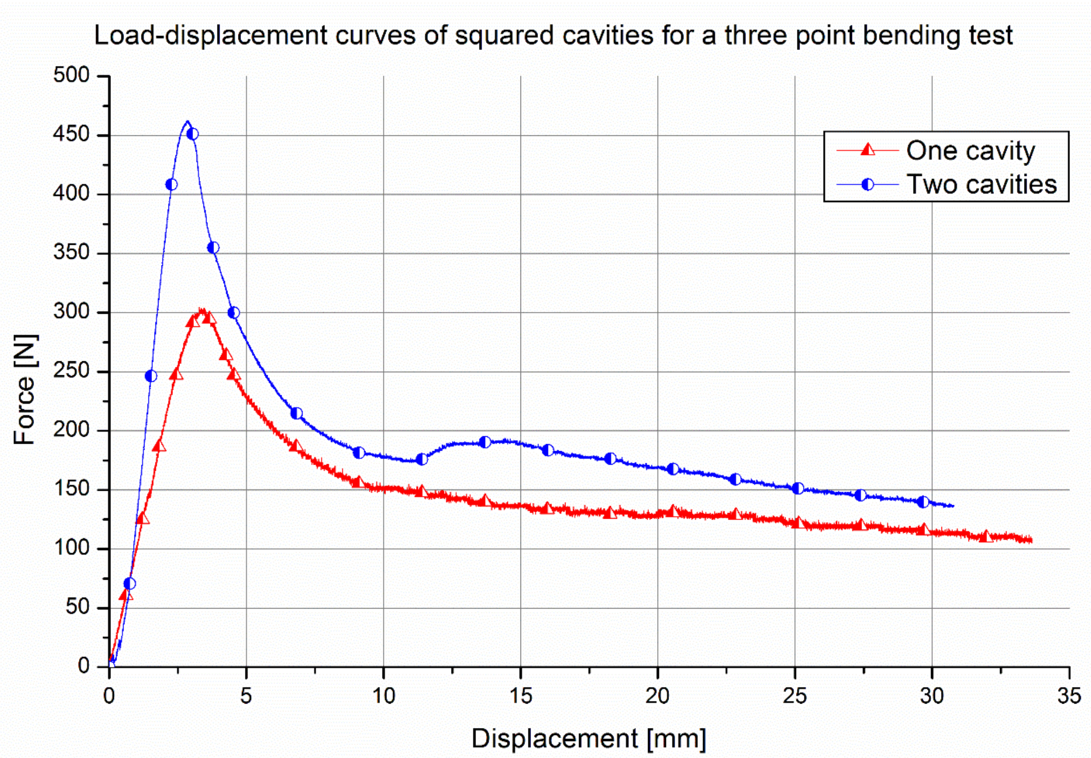


Figure 10. Comparison of a three point bending test for one and two squared cavities.

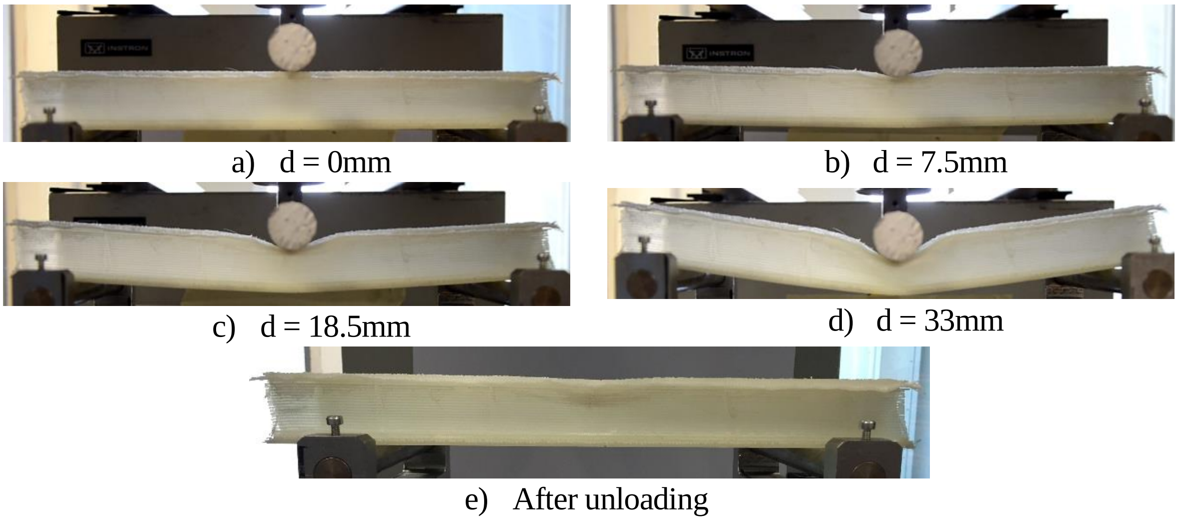


Figure 11. Illustration of the local indentation of one square cavity at the indenter at different displacements.

5 CONCLUSION

The presented woven fabrics with integrated prismatic shaped cavities are divided into two groups: profiled surfaces and flat surfaces. Within these two groups several geometries are produced of which only two were illustrated here. The production process of one composite of each group has been optimized for lab scale specimens. Three point bending tests have been performed on a filled and unfilled hexagonal cavity and on one and two unfilled squared cavities. All specimens fail due to local indentation at the indenter. The foamed hexagonal cavity reaches higher forces as the foam prevents local indentation at lower forces. It is worth mentioning that the polyester-polyester material combination has relative high residual strength and toughness. These first tests show very promising results and further investigation will be performed, also on larger components, to fully understand these textile structures and this new material combination.

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REFERENCES

[1] K. Fukuta and E. Aoki. *3D fabrics for structural composites*. in *15th textile reseach symposium*. 1986. Philadelphia.

[2] N. Khokar, *3D-weaving: Theory and practice.* Journal of the Textile Institute, 2001. **92**(1): p. 193-207.

[3] X.G. Chen, L.W. Taylor, and L.J. Tsai, *An overview on fabrication of three-dimensional woven textile preforms for composites.* Textile Research Journal, 2011. **81**(9): p. 932-944.

[4] X. Chen. *Technical aspect: 3D woven architectures*. in *NWTexNet*. 2007. Blackburn.

[5] G. De Clercq, et al., *Multirapier: A Weaving technology with available capacity towards the production of 3D fabrics*, in *4th world conference on 3D fabrics and their applications*. 2012: Aachen, Germany.
[6] X.G. Chen, Y. Sun, and X.Z. Gong, *Design, manufacture, and experimental analysis of 3D honeycomb textile composites Part I: Design and manufacture.* Textile Research Journal, 2008. **78**(9): p. 771-781.
[7] P.G. Unal, *3D woven fabrics*. 2012: INTECH Open Access Publisher.
[8] X. Gong. *Investigation of different geometric structure parameter for honeycomb textile composites on their mechnical performance*. 2011, The University of Manchester.
[9] M.Y. Wang, H.J. Cao, and K. Qian, *Mechanical Properties of Three-Dimensional Fabric Sandwich Composites.* Journal of Engineered Fibers and Fabrics, 2014. **9**(3): p. 1-7.
[10] A. Mountasir, G. Hoffmann, and C. Cherif, *Development of weaving technology for manufacturing three-dimensional spacer fabrics with high-performance yarns for thermoplastic composite applications: An analysis of two-dimensional mechanical properties.* Textile Research Journal, 2011. **81**(13): p. 1354-1366.
[11] S. Badawi. *Development of the weaving machine and 3D woven spacer fabric structures for leightweight composite materials*. [Dissertation] 2007, TU Dresden.
[12] A.W. van Vuure, J.A. Ivens, and I. Verpoest, *Mechanical properties of composite panels based on woven sandwich-fabric preforms.* Composites Part a-Applied Science and Manufacturing, 2000. **31**(7): p. 671-680.